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Sources and sinks of greenhouse gases in the landscape: Approach for spatially explicit estimates

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Sources and sinks of greenhouse gases in the landscape: Approach for spatially explicit estimates

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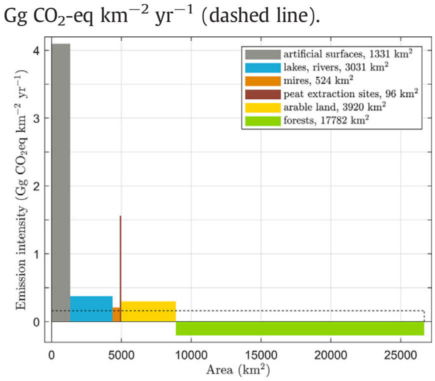
HIGHLIGHTS

- Local actions to mitigate climate change require data on the landscape scale.
- We combined information on anthropogenic and natural GHG sources and sinks.
- Fuel combustion and peat extraction were the most emission intensive activities.
- Aquatic ecosystems were as emission intensive as agricultural areas.
- Forests contributed the only significant sink in Kokemäenjoki river basin.

GRAPHICAL ABSTRACT

GHG emission intensity (Gg CO_2-eq km^{-2} yr^{-1}) versus area (km^2) by land cover type in Kokemäenjoki river basin, Finland. The net emissions for the entire river basin amounted to 4.37 ± 1.43 Tg CO_2-eq yr^{-1}, with an average net emission of 0.16 Gg CO_2-eq km^{-2} yr^{-1} (dashed line).



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ABSTRACT

Climate change mitigation is a global response that requires actions at the local level. Quantifying local sources and sinks of greenhouse gases (GHG) facilitate evaluating mitigation options. We present an approach to collate spatially explicit estimated fluxes of GHGs (carbon dioxide, methane and nitrous oxide) for main land use sectors in the landscape, to aggregate, and to calculate the net emissions of an entire region. Our procedure was developed and tested in a large river basin in Finland, providing information from intensively studied eLTER research sites. To evaluate the full GHG balance, fluxes from natural ecosystems (lakes, rivers, and undrained mires) were included together with fluxes from anthropogenic activities, agriculture and forestry. We quantified the fluxes based on calculations with an anthropogenic emissions model (FRES) and a forest growth and carbon balance model (PREBAS), as well as on emission coefficients from the literature regarding emissions from lakes, rivers, undrained mires, peat extraction sites and cropland. Spatial data sources included CORINE land use data, soil map, lake and river shorelines, national forest inventory data, and statistical data on anthropogenic activities. Emission uncertainties were evaluated with Monte Carlo simulations. Artificial surfaces were the most emission intensive land-cover class. Lakes and rivers were about as emission intensive as arable land. Forests were the dominant land cover in the region (66%), and the C sink of the forests decreased the total emissions of the region by 72%. The region's net emissions amounted to 4.37 ± 1.43 Tg CO_2-eq yr^{-1}, corresponding to a net emission

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intensity 0.16 Gg CO_2-eq km^{-2} yr^{-1}, and estimated per capita net emissions of 5.6 Mg CO_2-eq yr^{-1}. Our landscape approach opens opportunities to examine the sensitivities of important GHG fluxes to changes in land use and climate, management actions, and mitigation of anthropogenic emissions.

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1. Introduction

Climate change mitigation and adaptation are global responses that require actions at the local level. The Paris Agreement (UNFCCC, 2015) sets the scope for international efforts to limit the temperature increase to below 1.5 °C above pre-industrial levels, and the European Commission strives to achieve net-zero GHG emissions by 2050 (EC, 2018). Limiting and decreasing the accumulation of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases (GHGs) in the atmosphere implies a challenging mitigation agenda with high requirements for developed countries (Anderson et al., 2020). Solutions for improving energy efficiency of industries, municipalities and households are emerging (e.g. Vogl et al., 2021, Dalla et al., 2020, Putna et al., 2020, Solà et al., 2021) and the benefits of land-use actions such as rewetting peatlands and avoiding losing carbon by farming organic soil are clear (e.g. Costantini et al., 2020; Tanneberger et al., 2021). Net emissions of agriculture and forestry can be reduced through dietary changes and cultivation practices (Theurl et al., 2020), forest management and wood transport practices (Forsius et al., 2021; Palander et al., 2020). Local actors, such as cities, regions, businesses, public- private partnerships, residents and community groups, have important roles in shaping regional and municipal policies to mitigate climate change (Hillmer-Pegram et al., 2012; Broto, 2017). For mitigation to succeed, collaboration and network building are needed at different government levels and between public and private sectors (Amundsen et al., 2018). Globally, cities are substantial sources of GHGs and have the potential to promote successful mitigation (Gordon and Johnson, 2018). Local mitigation plans for European cities are emerging (Reckien et al., 2018; Palermo et al., 2020; Salvia et al., 2021). The activities of individual countries to comply with international and regional commitments (UNFCCC, 2015; EC, 2018) are documented annually in national inventory submissions (e.g. Statistics Finland, 2020). The official, mandatory national inventory required by the EU, UNFCCC and the Kyoto Protocol covers emissions and removals of direct GHGs from five sectors (energy; industrial processes and product use; agriculture; land use, land use change and forestry; and waste). The inventory report provides essential information for the planning and monitoring of national climate policies, e.g., detailed information on trends since 1990 (Statistics Finland, 2020). For local actors, the Finnish network for carbon-neutral municipalities and its partner projects offer opportunities to share information and engage in testing and developing mitigation solutions in production and consumption, urban development, housing, forestry and agriculture (Heiskanen et al., 2015; Carbonneutral Finland, 2020).

The carbon (C) cycle of terrestrial and aquatic ecosystems is of central importance in regulating the GHG concentration of the atmosphere (Chapin III et al., 2006; Cole et al., 2007; Tranvik et al., 2009; Aufdenkampe et al., 2011; Raymond et al., 2013; Nakayama, 2017). Although land use change or intensive land management practices may have negative climate impacts, management strategies also have a remarkable mitigation potential (Costantini et al., 2020, Tanneberger et al., 2021).The net emissions of a region are determined by the area of different land cover types as well as their area-specific emissions. Forest net ecosystem exchange (NEE) has been found to be the largest regional C flux, amounting to about 90% of the sink, but also the wetland, lake and riverine C fluxes are of consequence to the overall budget in temperate (Buffam et al., 2011) and boreal (De Wit et al., 2015) landscapes. Magin et al. (2017) discovered that on average 1.31% of terrestrial NPP (net primary productivity) was emitted as CO_2 from the stream network and 1.49% was discharged downstream as dissolved inorganic carbon (DIC), which was the dominant form of C in these temperate streams. In Finland, forests take up about 30% of the GHG emissions annually depending mainly on the volume of harvest removal (Statistics Finland, 2020). To enhance forest productivity, a major area of Finnish peatlands has been drained, which led to complex consequences on their GHG balance (Ojanen et al., 2013). According to the soil inventories, croplands have lost C in 1974–2009 (Heikkinen et al., 2013). The GHG balance of arable land is affected by climatic conditions and agricultural management practices, such as tillage and fertilization (Lugato et al., 2014; Singh et al., 2015). Cultivated organic soils are a major source of agricultural greenhouse gas emissions in Finland although they cover only 10% of the field area (Regina et al., 2019). Lakes and rivers play an important role in C cycling, as they process, emit and transport substantial amounts of C from the catchment area, and ignoring inland water CO_2 evasion could cause significant errors in regional-scale budgets (Aufdenkampe et al., 2011, Raymond et al., 2013, Nakayama, 2017).

Quantifying the vertical fluxes from different land cover classes, such as fields, forests, mires, water bodies and built environment is of key importance in order to facilitate evaluating plausible climate change mitigation strategies and adaptation options. Combining process-based models, empirical emission coefficients and land cover data is a useful approach for quantifying the effects of human activities on the regional GHG balance (Buffam et al., 2011; De Wit et al., 2015). Maps facilitate the perception of scales and provide an overview of the origin of emissions and the C sink capacity of various ecosystems. Maps may also be utilized in drafting paths towards achieving C neutrality at a regional or municipal level (e.g. Kekkonen et al., 2019; Moomaw et al., 2020). In this paper we present an approach to aggregate vertical GHG fluxes from terrestrial and aquatic ecosystems. Our work has evolved from a study of land use related and anthropogenic GHG emissions on the municipal level (Vanhala et al., 2016; Haaspuro, 2013). In the current approach, we apply the FRES regional emissions model to anthropogenic sources, the PREBAS forest growth and carbon exchange model to sources and sinks in forests, and area-specific emission coefficients from the literature for sources and sinks in lakes, rivers, undrained mires, peat extraction sites, and arable land. Here, a boreal river basin in southwestern Finland is used as an example case of combined terrestrial and aquatic GHG flux analysis. Similar map series, with corresponding aggregation of data and results, may be produced for the local, regional or national scale depending on the information needs. This paper presents a means to collate spatially explicit estimates of GHG emission sources and sinks for main land use sectors in the landscape, to aggregate and calculate the net emissions for the region. We discuss the role of the different land cover types and evaluate the uncertainties of the sector-specific estimates.

2. Material and methods

2.1. Study region

Kokemäenjoki river basin in western Finland has a varying land cover and long-term ecological research has been carried out in the area (Rask et al., 2014; Forsius et al., 2016). The river basin covers about 27,125 km^2, or 8% of the country total. The land cover types in the river basin include artificial surfaces (population centres, industrial and energy production plants, roads and other infrastructure constructions), waterbodies (lakes of different sizes, rivers of varying width), wetlands (ombrotrophic and minerotrophic undrained mires, peat extraction sites), agricultural areas (arable land on mineral and organic soil, domestic livestock production units), and forests and semi-natural areas (pine, spruce and hardwood forests on mineral soil and on peatland) (Fig. 1, Table 1). The vegetation zones of the region are middle and southern boreal covering 20 and 80% of the area, respectively (Nordic Council of Ministers, 1984). The study region overlaps partly with eight regions on the third level of aggregation, NUTS 3 (EC, 2020). Pirkanmaa, Kanta-Häme and Satakunta show the largest areas (97%, 88%, 30%, respectively) within the boundaries of Kokemäenjoki river basin (Table A1). There are altogether 69 municipalities located at least partly within the study region, and 26 of them are entirely within the borders of the river basin. Adjusting for the fraction of municipality area within the river basin, the population was approximately 780,000 in 2020, or 14% of the country total. With three major cities in the region, Hämeenlinna and Tampere entirely, and the central parts of Pori, although only 22% of the city's area, the estimated population density was about 29 per km^2, compared with an average of 18 per km^2 for Finland.

The spatial allocation was based on polygons (lakes, undrained mires, cropland), polylines (rivers), and rasters (artificial surfaces, forests). Information on the sources of spatial data is given in Supplementary Table A2.

2.2. Greenhouse gas fluxes and emission intensities

For each land cover type the average annual net emissions of one or several GHGs (CO_2, CH_4, N_2O, depending on the key processes occurring in respective ecosystems) were calculated as the sum of sources (positive emissions) and sinks (negative emissions). The annual emissions represent best estimates of current conditions, allowing for some variation in the time frames of the available data (Table A2). The net emission intensities of the study region, and each of its land cover types, were derived by dividing the net emissions with corresponding surface area.

Table 1
Area of land cover types in Kokemäenjoki river basin.

Land use	Area (km^2)	Area (%)
Artifical surfaces	1331	4.9%
Lakes, rivers	3031	11.2%
Mires	524	1.9%
Peat extraction sites	96	0.4%
Arable land	3920	14.5%
Forests	17,782	65.6%
Other	441	1.6%
Total	27,125	100.0%

Annual vertical fluxes of GHGs between the atmosphere and land, vegetation or water surfaces were calculated with area-specific emission factors (lakes Section 2.4.1, rivers Section 2.4.2, mires and peat extraction sites Section 2.5, arable land Section 2.6), and models (artificial surfaces Section 2.3, forests Section 2.7). The total annual lateral flux of organic and inorganic C from the river basin to the sea was obtained from literature, and a qualitative estimate of the leaching of C from terrestrial areas to water courses was based on a model application (Section 2.4.3). These estimates of lateral fluxes were not coupled to the calculations of vertical fluxes, however, only presented in order to describe the river basin characteristics. In terms of methodological complexity (IPCC, 2006a), our approach corresponded to tiers 2 (lakes, rivers, mires, peat extraction sites, arable land, artificial surfaces) and 3 (forests).

The different gases (x) contributing fluxes of elements (y) to the atmosphere were converted to carbon dioxide equivalents (CO_2-eq) in order to express the fluxes in comparable units. Emissions of elements $y = C$ or N expressed as gC m^{-2} yr^{-1} or gN m^{-2} yr^{-1} were first converted to gCO_2, gCH_4 or gN_2O, depending on which gas (x) flux the

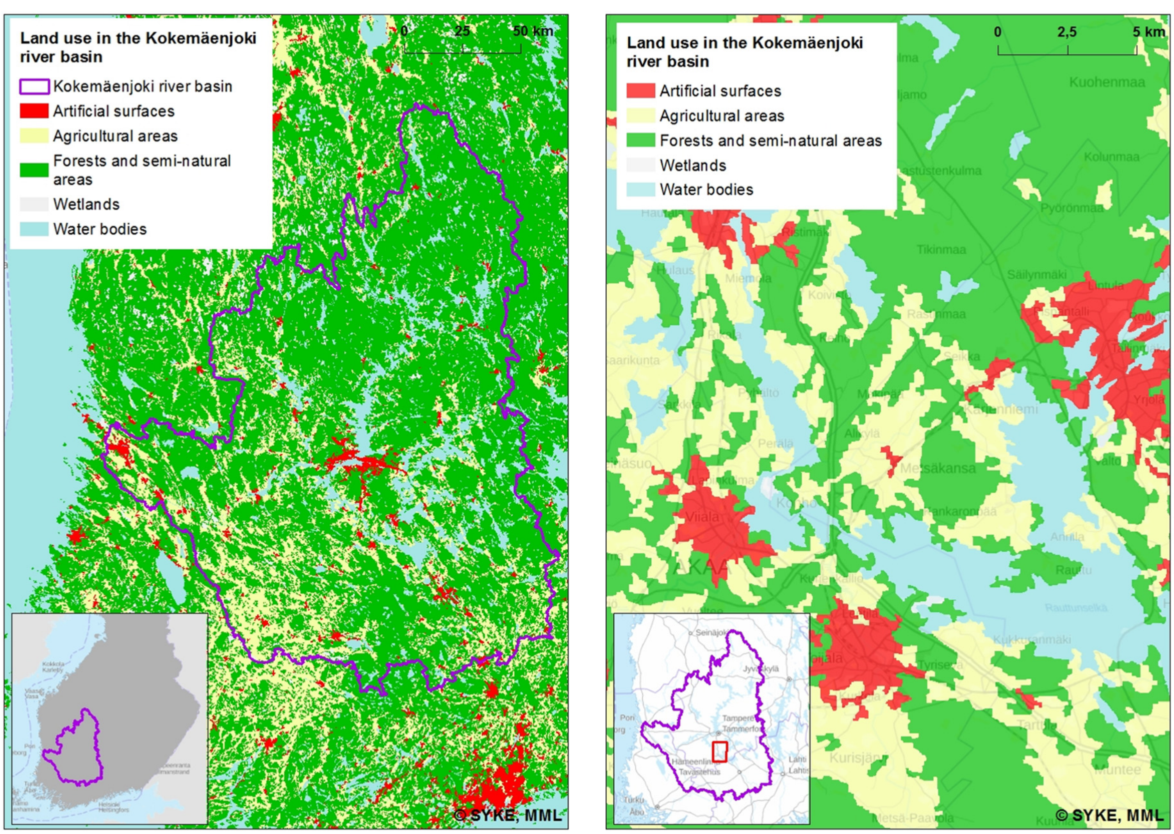

Fig. 1. Location of Kokemäenjoki river basin and main land cover classes (CORINE, 2012).

emissions were related to. Then the emissions were multiplied with the relative warming potential (GWP_x) of each gas (IPCC, 2014; Myhre et al., 2013). Compound molar masses of gases (M_x) were also used in the conversion (Table A3), and the results were shown as g CO_2-eq m^{-2} yr^{-1} on the maps, or as Tg CO_2-eq yr^{-1} for larger areal units. The emission intensities were expressed as Gg CO_2-eq km^{-2} yr^{-1}.

We calculated fluxes of GHGs as positive numbers (sources) when the flow direction was from land or water surfaces to the atmosphere, and negative numbers (sinks) in the opposite case. Sources of GHGs in this study included anthropogenic emissions of CO_2, CH_4 and N_2O from point or area sources; evasion of CO_2 from lake and river surfaces; diffusion and ebullition of CH_4 from lakes and wetlands; emissions of CO_2, CH_4 and N_2O from undrained mires; emissions of CO_2 and N_2O from arable land; and emissions of CO_2 from forest ecosystems. The sinks of GHGs that we considered included assimilation of C in growing forest vegetation, as well as sequestration of C in forest mineral soils.

The net emissions for the entire river basin E_{KRB_net} (Tg CO_2-eq yr^{-1}) were calculated by summing the net emissions for each type of land cover (Eq. (1)).

$$E_{KRB\_net} = E_{Ant\_net} + E_{L\_net} + E_{R\_net} + E_{M\_net} + E_{Pe\_net} + E_{A\_net} + E_{F\_net}, \quad (1)$$

where the terms represent the net emissions from artificial surfaces, lakes, rivers, mires, peat extraction sites, arable land, and forest, as described below in Sections 2.3 to 2.7. In the aggregation, we only considered vertical fluxes of GHGs. The fluxes from terrestrial to aquatic ecosystems (Section 2.4.3) were approximated in order to provide background information on the river basin characteristics.

To quantify the uncertainties of the emissions from sources and sinks in the river basin we followed the recommendations given in IPCC guidelines for natural GHG inventories (IPCC, 2006b). Normal distributions of area- and source-specific emission factors were used to validate the uncertainties in resulting area-based emissions, except where specified otherwise. Monte Carlo simulations, with 10^6 repetitions, were used to estimate the mean and 95% confidence interval for source-specific emission for each land cover class, total emissions for each land cover class, and the total emissions for the study region, following the error propagation rules of IPCC (2006b). In the case of forests, the uncertainty was estimated qualitatively, and the uncertainty quantification was based on expert judgment. Uncertainty in artificial surface emissions was based on information on the combined uncertainty of activity data and emission coefficients given as source- and GHG-specific estimates (Statistics Finland, 2020).

2.3. Artificial surfaces

Annual anthropogenic CO_2, CH_4 and N_2O emissions originating from fuel combustion were calculated with the Finnish Regional Emission Scenario (FRES) model developed at the Finnish Environment Institute (Karvosenoja, 2008). To avoid double-counting with respect to emissions from harvested biomass, we did not include CO_2 emissions from the biomass combustion. Due to incomplete combustion, e.g. in low temperatures of residential burners, some C is emitted in the form of CH_4, which is associated with a 28 times higher climate warming potential than CO_2. The emission of CH_4 was included, as it occurs in addition to the stock change estimate (as harvested biomass), following the IPCC Guidelines (IPCC, 2019).The emissions were given separately for point sources that were aggregated to municipal level and gridded area emission sources on 250 m × 250 m horizontal grid resolution.

2.3.1. Point sources

Emissions from fuel combustion in energy production and industrial plants located within 34 of the 69 municipalities in the region were aggregated into point sources on the municipal level (Table A4a). The point source emissions of individual plants in the FRES-model were averages over several years and thus not identical to the officially reported annual emissions of certain individual years in the environmental emissions data base. Only point sources located within the Kokemäenjoki river basin were included for each municipality, and the total emissions of point sources E_{P_tot} were calculated as in Eq. (2).

$$E_{P\_tot} = \sum_{m=1}^{34} \sum_{s=1}^{5} \left(E_{P\_CO2\_s\_m} + GWP_{CH4} \cdot E_{P\_CH4\_s\_m} + GWP_{N2O} \cdot E_{P\_N2O\_s\_m}\right), \quad (2)$$

which sums the emissions ($E_{P\_x\_s\_m}$) of each gas (x) over five fuels (s) and 34 municipalities (m) (Table A4a). The fuels used in combustion were liquid fuels, waste and other solids, gaseous fuels, peat and biomass. In the case of biomass, only emissions of CH_4 and N_2O were included in our calculations, to avoid double-counting with CO_2 emissions of removals of wood from forests (Section 2.7.). The coefficients GWP_x relate to the warming potential of gases x (Table A3).

2.3.2. Area sources

Emissions from fuel combustion in domestic heating, road transport, machinery and other transport were obtained as gridded area sources. The FRES model uses several proxies to estimate the spatial distribution of the area source emissions (Paunu et al., 2013; Karvosenoja et al., 2018). The main data sources for the proxies were Digiroad for roads and traffic volumes, The National Buildings and Dwellings Register for buildings data, and CORINE2012 for land use data. The area sources of the artificial surfaces were aggregated to four sectors: traffic exhaust (CO_2), machinery and off-road vehicles (CO_2), small scale wood combustion (CH_4, N_2O) and other small-scale combustion (CO_2) (Table A4b) and the total area sources were summed as in Eq. (3) over N_a = 434,020 grid cells

$$E_{G\_tot} = \sum_{n=1}^{Na} \sum_{z=1}^{4} \left(E_{G\_CO2\_z\_n} + GWP_{CH4} \cdot E_{G\_CH4\_z\_n} + GWP_{N2O} \cdot E_{G\_N2O\_z\_n}\right), \quad (3)$$

which sums the gridded emissions ($E_{G\_x\_s\_m}$) of each gas (x) over four types (z) of emissions for each grid cell (n) (Table A4a). The coefficients GWP_x relate to the warming potential of gases x (Table A3). To avoid double-counting, we did not include CO_2 emissions from the biomass combustion. Due to incomplete combustion, e.g. in low temperatures of residential burners, some C is emitted in the form of CH_4, which is associated with a 28 times higher climate warming potential than CO_2. The emission of CH_4 was included, as it occurs in addition to the stock change estimate (as harvested biomass), following the IPCC Guidelines (IPCC, 2019). Note that only the emission types z = 1–4 are summed in this paper with the other grid-specific emissions (Table A4a), while the fifth emission type, agriculture, for which FRES also calculates emissions, is reported in connection with land-use related emissions from arable land (Section 2.6.4).

Total emissions from anthropogenic emissions are then obtained as the sum of point source and area sources (Eq. (4)),

$$E_{Ant\_net} = E_{Ant\_tot} = E_{P\_tot} + E_{G\_tot}. \quad (4)$$

As no sinks are related to anthropogenic activities in the region, the net emissions equal the total emissions for anthropogenic sources.

The uncertainty of the emissions from the land cover class artificial surfaces was based on source and GHG -level uncertainty intervals (Table A4b). The uncertainty intervals were results of activity data and emissions coefficient uncertainties given in Statistics Finland, 2020 (Annex 2. Assessment of uncertainty, Table 1). In case of asymmetric uncertainty intervals, the larger percentage difference between the mean and confidence limit was used.

2.4. Aquatic ecosystems

2.4.1. Lakes

Kokemäenjoki river basin includes altogether $N_L = 14{,}804$ lakes with a total surface area of 2933 km^2. Most lakes have a surface area smaller than 0.1 km^2, only four lakes have a surface area larger than 100 km^2 (Table A5a). Five lake size classes were considered for the emission calculations: smaller than 0.1 km^2, 0.1–1, 1–10, 10–100 and lakes larger than 100 km^2, based on a regionally representative, randomly selected lake database of Finnish lakes with data of 200 lakes smaller than 100 km^2 (Kortelainen et al., 2006; Juutinen et al., 2009) and all lakes larger than 100 km^2 (Rantakari and Kortelainen, 2005).

Total emission of GHGs from lakes E_{Ltot} (Tg CO_2-eq yr^{-1}) were obtained as the sum over five lake size classes (Eq. (5)),

$$E_{L\_tot} = \sum_{i=1}^{5} A_i \cdot \left[M_{CO2} \cdot M_C^{-1} \cdot C_{L\_CO2\_i} + GWP_{CH4} \left(M_{CH4} \cdot M_C^{-1} \cdot \left(C_{L\_D\_CH4\_i} + C_{L\_E\_CH4\_i} \right) + C_{L\_mc\_i} \cdot \left(\sum_{j=1}^{2} \cdot C_{Sp\_j} \cdot C_{Veg\_CH4\_j} \right) \right) \right], \tag{5}$$

where A_i is surface area, and the sub-index i refers to lake size class i ($i = 1$–5). M is molar mass and GWP is global warming potential (Table A3). In Eq. (5), the area-specific CO_2 net evasion $C_{L\_CO2\_i}$ (gC m^{-2} yr^{-1}) flux rate coefficients for each of the five lake size classes i (Table A5b) were obtained from a study by Kortelainen et al. (2006). Area-specific estimates for CH_4 diffusion from lakes $C_{L\_D\_CH4\_i}$ (gC m^{-2} yr^{-1}) were calculated by Juutinen (unpublished) based on the data in Juutinen et al. (2009), also for five lake classes (Table A5b). The contribution of CH_4 ebullition to the lake GHG balance $C_{L\_E\_CH4\_i}$ (gC m^{-2} yr^{-1}) was estimated on the basis of a study on Swedish lakes (Bastviken et al., 2004), also in relation to lake size (Table A5b; Note 1). Emergent macrophytes have a considerable impact on methane emissions from lakes, in Finland especially two species are important: *Phragmites australis* and *Equisetum fluviatile* (Bergström, 2011). For each of the five lake classes, the fraction of the lake surface covered by emergent macrophytes $C_{L\_mc\_i}$ (m^2/m^2) was determined using the method by Bergström et al. (2007). On the average, 37% of the vegetation covered surface area was assumed to be dominated by *Phragmites* (C_{Sp_1}), and 45% by *Equisetum* (C_{Sp_2}) (Bergström et al., 2007). Methane evasion coefficients $C_{Veg\_CH4\_j}$ (gC m^{-2} yr^{-1}) were determined by Juutinen (unpublished) for each species j (Table A6) using data of Juutinen et al., 2003.

2.4.2. Rivers

About 9000 stream segments from 2 m to 5 m wide were identified as polylines, their average width was assumed to be 3.5 m. Around 1000 river segments wider than 5 m were read as polygons, their surface area was estimated as half of the polygon area divided by its length. The total area of rivers and streams in Kokemäenjoki river basin was estimated to 98 km^2 (Table A7a). The data used in the calculation of the river segment surface areas was based on the national river bed database (Finnish Environment Institute, 2019). For rivers, the total CO_2 emission estimate E_{R_tot} (Tg CO_2-eq yr^{-1}), was obtained by summing for each of the four river size classes the product of surface area of rivers and the estimated CO_2 fluxes for individual stream orders following the method by Humborg et al. (2010) using flux rate parameters given in Table A7b. No sinks were considered for rivers, so the net emissions equalled the total emissions (Eq. (6)),

$$E_{R\_net} = E_{R\_tot} = M_C^{-1} \cdot M_{CO2} \cdot \sum_{k=1}^{4} A_k \cdot C_{R\_CO2\_k}, \tag{6}$$

where A_k is the surface area, and $C_{R\_CO2\_k}$ is the flux rate parameter of river size class k.

2.4.3. Fluxes from terrestrial to aquatic

The total export from the river basin to the sea was estimated from monitoring data for Finnish rivers (Räike et al., 2016). The flux of organic carbon from terrestrial ecosystems to lakes and rivers was estimated with the process-based dynamic INCA-C model (Futter et al., 2011). The INCA-C was applied to the Pääjärvi catchment in Lammi within Kokemäenjoki river basin. Lake Pääjärvi and its catchment is an LTER site with dense and good quality data (e.g. Bergström et al., 2007; Rankinen et al., 2013). The Pääjärvi INCA-C application was upscaled to the whole Kokemäenjoki river basin for an approximation of the amount of organic carbon leaching from cropland, forests and mires to the watercourses.

2.5. Wetland

Emissions from wetland were calculated explicitly for undrained mires (Section 2.5.1) and peat extraction sites (Section 2.5.2), while peatlands drained for forestry were included in the net emissions for forests (Section 2.7.2).

2.5.1. Undrained mires

Undrained peatlands were selected from the national peatland GIS data set by SYKE which was directly derived from the Topographic Database (version 2008) by the National Land Survey of Finland. Undrained mires were classified into minerotrophic and ombrotrophic peatlands (Table A8a) by using the MS-NFI data layers (version 2013; Tomppo et al., 2014). For undrained mires in the Kokemäenjoki river basin, the net emissions of GHGs E_{M_net} (Tg CO_2-eq yr^{-1}), were calculated as the sum of net emissions of CO_2, total emissions of CH_4 and N_2O (Eq. (7)),

$$E_{M\_net} = \sum_{u=1}^{2} A_u \cdot \left(C_{M\_CO2\_u} + C_{M\_CH4\_u} + C_{M\_N2O\_u} \right), \tag{7}$$

where A_u is the surface area of each type of mire. The net emission coefficients of undrained mires $C_{M\_CO2\_u}$, $C_{M\_CH4\_u}$ and $C_{M\_N2O\_u}$ (g CO_2-eq m^{-2} yr^{-1}) were annual average values derived from observed data on C balance, the leaching of dissolved organic C, source of CH_4 (Minkkinen and Ojanen, 2013; Minkkinen et al., 2018), and source of N_2O (Minkkinen et al., 2020) (Table A8b; Eq. (7)).

2.5.2. Peat extraction sites

Total emissions of CO_2, CH_4 and N_2O from peat extraction sites E_{Pe_tot} (Tg CO_2-eq yr^{-1}) were calculated with emission factors used in the national GHG inventory (Statistics Finland, 2020). The emission factors (Table A9) represent fluxes of CO_2, CH_4 and N_2O (C_{PCO2}, C_{PCH4}, C_{PN2O}) from stockpiles, ditches and production and the values have been derived from Nykänen et al. (1996) and Alm et al. (2007) (Statistics Finland, 2020). For CO_2, the emission factors of the south boreal zone for the period 1990–2014 were used, for CH_4 and N_2O, the estimates for the period 1900–2015. The area ($A_{Pe} = 96$ km^2) of peat extraction sites in the Kokemäenjoki river basin was compiled from the CORINE, 2012 GIS data. Again, no sinks were considered for this land cover type, and the net emissions equalled the total emissions (Eq. (8)),

$$E_{Pe\_net} = E_{Pe\_tot} = A_{Pe} \cdot \left(C_{Pe\_CO2} + C_{Pe\_CH4} + C_{Pe\_N2O} \right). \tag{8}$$

2.6. Arable land

2.6.1. Emission calculation in arable land

The sources of GHG emissions in arable land are cropland C stock change and N_2O emissions. The emissions for each field plot in arable land were calculated by multiplying the corresponding area specific emission coefficient by the area of the field plot. The values of the emission coefficient depend on the type of soil of each field plot (either mineral or organic), and the type of crop cultivated (Table A10a). The area of cropland comprises the land area used for arable crops, grass (rotational), permanent horticultural crops, greenhouses, kitchen gardens and set-aside (Statistics Finland, 2019).

The spatial distribution of mineral and organic soils in Kokemänjoki river basin was determined from the soilscapes of the national digital soil map (Lilja et al., 2017). Organic soils were here defined to include Umbric Gleysols and Sapric Histosols, while mineral soils were the other mapped soilscapes (Arenic Podzols, Stagnic Regosols, Vertic Luvic Stagnosolz, Endogleyic Podzols). The digital soilscapes were available from 2010 in the internal geodata portal of the Finnish Environment Institute. The national digital plot field register was used for cropland on organic soil to distinguish between grassland and annual crops. Information from this register was used for the situation of 31.3.2017, available in the internal geodata portal of the Finnish Environment Institute. All other crops than grass were considered annual. The surface area of cultivated organic soils in active use in Kokemäenjoki river basin is 182 km^2, from which 69.9% is cropland with annual plants, and the rest is cropland with perennial plant species.

2.6.2. Carbon stock changes in cropland

The emissions of CO_2 from cropland were estimated separately for mineral soils and organic soils (Table A10b), in accordance with the national reporting of greenhouse gases (Statistics Finland, 2019). For cropland on mineral soils, the area specific coefficient for C emissions was an average value of the annual changes in soil carbon stock simulated with the Yasso07 model (Palosuo et al., 2015) for southern Finland for the years 2002–2017 (0.058 ± 0.037 Mg C ha^{-1} a^{-1}), as reported in the national GHG inventory report (Statistics Finland, 2019 Table 3_App_6j). For grasses and annual crops on organic soils, area specific emission coefficients for Southern Finland 5.7 Mg C ha^{-1} a^{-1} and 7.9 Mg C ha^{-1} a^{-1} were used, respectively (Statistics Finland, 2019).

2.6.3. Nitrous oxide emissions from agricultural soils

The direct N_2O emissions from organic agricultural soils in this study are calculated using the same 2006 IPCC Guidelines' methodology and country specific emissions factors as were used in the National inventory report of Statistics Finland (2019), Table 5.4-8 (IPCC, 2006c). Emissions of organic soils cultivated with annual plants are calculated using the emission factor (Table A10b) given in the report IPCC Wetlands Supplement for drained organic croplands in boreal and temperate climate/vegetation zones was used (IPCC, 2014, Chapter 2, Table 2.5), 13.0 kg N_2O-N ha^{-1} $year^{-1}$. The emission factor for actively cultivated fields on organic soil with perennial plants is the default for boreal drained grassland from the same table, 9.5 kg N_2O-N ha^{-1} $year^{-1}$.

The net land use related emissions of CO_2 and N_2O from arable land were calculated as Eq. (9),

$$E_A = M_{CO2} \cdot M_C^{-1} \cdot \left(A_1 \cdot C_{A_{CO2_1}} + \sum_{q=1}^{2} A_{2_q} \cdot C_{A_{CO2_{2_q}}} \right) + GWP_{N2O} \cdot M_{N2O} \cdot M_N^{-1} \cdot \sum_{q=1}^{2} A_{2\_q} \cdot C_{A\_N2O\_2\_q}, \quad (9)$$

where the conversion factors M_x, M_y are molar masses, and GWP_{N2O} relates to the warming potential of N_2O (Table A3). Surface areas, and net CO_2 emission flux rates, of cultivated fields on mineral and organic soil are denoted with A_1 and A_{2_q}, and $C_{A\_CO2\_1}$, and $C_{A\_CO2\_2\_q}$, respectively. The net N_2O emission flux rates of organic soil fields are denoted with $C_{A\_N2O\_2\_q}$. In Eq. (9), the subscript $q = 1$ represents annual, and $q = 2$ perennial crops on organic soil fields (Tables A10a, A10b).

2.6.4. Methane and nitrous oxide emissions from agricultural sector

Emissions from anthropogenic activities in the agricultural sector were calculated with the FRES-model as described for artificial surfaces (Section 2.3.2). Area emissions from the agricultural sector originate from domestic livestock production (enteric fermentation CH_4; manure N_2O) (Tables A4a, A4b). Emissions from enteric fermentation were based on country-total emissions from domestic livestock, allocated to each municipality in proportion to the livestock volume, and distributed spatially within the municipalities following the distribution of arable land (CORINE, 2012, Level 2, Class 2.1. Arable land). Emissions from manure were based on country-total volume of manure, which was spatially allocated according to the distribution of arable land. The emissions were summed for all grid cells of the artificial surfaces ($N_a = 434{,}020$) (Eq. (10)),

$$E_{G\_5} = \sum_{n=1}^{Na} (GWP_{CH4} \cdot E_{G\_CH4\_5\_n} + GWP_{N2O} \cdot E_{G\_N2O\_5\_n}). \quad (10)$$

In Eq. (10), it is to be noted that the emissions equal zero for grid cells not overlaying arable land. The net emissions of arable land E_{A_net} (Tg CO_2-eq yr^{-1}) were obtained by summing the land use related emissions E_A with the gridded emissions for the agricultural sector calculated by FRES E_{G_5}, (Eq. (11)),

$$E_{A\_net} = E_A + E_{G\_5}. \quad (11)$$

2.7. Forest

2.7.1. Forest data

Forests in Kokemäenjoki river basin grow both on mineral soil (77%) and peatland (23% of the forest area), with a mean volume of 155 m^3 ha^{-1} and a mean annual growth of 7.1 m^3 ha^{-1}. Pine and spruce each represent about 40% of the total volume of the growing forest in the region, and birch and other hardwood the remaining 20% (National Forest Inventory 2012–2014). The state of forests at the beginning of forest carbon balance simulations was based on MS-NFI (Multi-Source National Forest Inventory) maps, which describe the forest parameters in the form of thematic maps across Finland at 16×16 m resolution. MS-NFI maps are based on combining the information of NFI field plot measurements, satellite imagery and digital map data (Tomppo et al., 2008a, 2008b). Forest data was further segmented to homogeneous units (henceforth forest parcels), which were simulated with PREBAS model.

Removals from forests describe the total amount of harvested wood, and thus, they are an important part of the forest carbon balance. Data of annual removals during the simulation period were obtained from the Luke Statistics service (OSF, 2019), which collects harvest information from companies and citizens across Finland. Annual removals are reported for 19 administrative regions in Finland by tree species and wood type (logs, pulp, energy-wood). The Kokemäenjoki river basin overlaps with eight administrative regions. The removals for the river basin were calculated by weighing the regional totals with the region's share of the total forest land area.

2.7.2. Forest carbon balance

The carbon emissions from the forested areas in Kokemäenjoki river basin were based on the results of the forest growth and carbon balance model PREBAS, which combines a forest growth model (Valentine and Mäkelä, 2005), and a forest gas flux model (Peltoniemi et al., 2015). The gas flux model has been calibrated using information on GPP and water balance at 10 eddy covariance sites in Scandinavia (Minunno et al., 2016) and the whole PREBAS model was recently calibrated using growth experiments in Finland (Minunno et al., 2019). Uncertainties in PREBAS modelling results are caused by uncertainties in input data, which consists of initial state estimation, weather drivers, and applied forest management, and model uncertainty due to parametric uncertainty and uncertainties about model structure. Previous studies with PREBAS have found output uncertainties due to parametric uncertainty to be rather small, whereas uncertainties due to model structural error, weather and forest management scenarios can potentially be substantial, especially when making long-term simulations with climate change and forest management scenarios (Kalliokoski et al., 2018; Mäkelä et al., 2020). Here, our simulation period is rather short, information about the forest state and management intensity follows forestry statistics, and we use current weather only. We conclude that forest initial state uncertainty is likely the largest, albeit the least understood uncertainty component in this analysis. The main quantifiable uncertainties in the NEE calculation are due to year-to-year variability of weather and growing stock, which varies due to the timing of harvests. The annual NEE varies accordingly, which also creates some uncertainty in the long-term mean NEE. We estimate the uncertainty of the mean to be ±10%. The uncertainties related to the average removals can be estimated to be of the same order of magnitude, as uncertainty of allocating the removals may cause feedbacks due to wrong species or site productivities of the removals.

PREBAS calculated the net ecosystem exchange, NEE, (gC m^{-2} yr^{-1}) for current climate conditions and with standard forest management, and the amount of harvested biomass (gC m^{-2} yr^{-1}). The harvested amount for each simulation year was specified by removals statistics, as described in Section 2.7.1. Removals data defined the total amount of harvests in the study region. Harvests were allocated into simulated forest parcels according to the stand mean diameter and age criteria specified in the national forest management guidelines (Sved and Koistinen, 2015). In the case of forests growing on upland soils, the PREBAS model is linked to the soil carbon model YASSO (Tuomi et al., 2009, 2011), which estimated soil respiration. For forests on drained peatland soils, soil respiration estimates were based on measured soil respiration, which includes both peat decomposition and litter decomposition (or accumulation) (Minkkinen et al., 2018; Ojanen et al., 2010, 2013, 2019). We did not include any forest soil sink of CH_4 in our calculations, as this is not expected to contribute significantly to the overall GHG balance for upland boreal forest soils (Dalal and Allen, 2008; Gatica et al., 2020).

Total NEE was calculated as a sum of vegetation and soil fluxes. It is positive when the C flux from the decomposition of soil organic matter is larger than the assimilation of C into growing vegetation and soil, and negative when the assimilation of C into growing vegetation and soil is larger than the C flux from decomposing soil organic matter. The net emissions of forests were calculated by summing NEE and the harvest removals, for each calculation pixel ($N_f = 69{,}460{,}000$) with the size of $A_{gf} = 256\ m^2$ (Eq. (12)),

$$E_{F\_net} = M_{CO2} \cdot M_C^{-1} \cdot A_{gf} \cdot \sum_{n=1}^{Nf} \left(NEE_n + E_{F_{harvestn}} \right). \qquad (12)$$

The focus of our calculations is on the flux between the atmosphere and vegetation and soil. In our calculations, all harvested biomass is considered emissions, although only part of it is harvested for bioenergy, around 17% on average. We do not account for carbon stored in wood-based products because our analysis does not include life-cycle calculations or the import or export of carbon to or from the region. Net emissions are positive when the forest acts as a source of CO_2 to the atmosphere, and negative when the forest is a sink.

3. Results

3.1. Emissions of the entire river basin

The role of the different land cover types in the region was illustrated by an areal emission intensity diagram, plotting the emission intensity (Gg CO_2-eq km^{-2} yr^{-1}) against the surface area (km^2) of each land cover type (Fig. 2). The region's total net emissions 4.37 ± 1.43 Tg CO_2-eq yr^{-1} equal the sum of the emission intensities times the area of each land cover type. The average net emission intensity was 0.16 Gg CO_2-eq km^{-2} yr^{-1} (Table 2). Dividing the net emissions of the Kokemäenjoki river basin with its estimated population for 2020 (780000) yielded a per capita net emission intensity of 5.6 Mg CO_2-eq yr^{-1}.

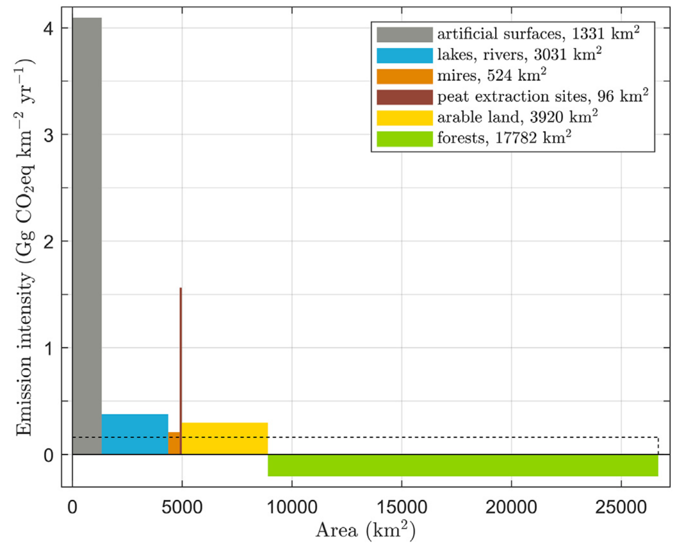

Fig. 2. Emission intensities (Gg CO_2-eq km^{-2} yr^{-1}) by land cover type. The dashed line represents the average net emission intensity 0.16 Gg CO_2-eq km^{-2} yr^{-1}. The net emissions for the entire river basin amounted to 4.37 ± 1.43 Tg CO_2-eq yr^{-1}.

Artificial surfaces were by far the most emission intensive land-cover class (Fig. 2), but because of their relatively small surface area (5%), they contributed only about one third of the total GHGs emissions of the region. Lakes and rivers were about as emission intensive as arable land, and with similar surface areas (11 and 15% respectively), each contributed about 7% to the total emissions (Table A11). A minor sink was the accumulation of C into undrained mires. Undrained mires were, however, not frequent in the area, so although they were low in intensity they decreased the entire region's emissions by less than 1%. Peat extraction sites had high emission intensity but small surface area. Removal of wood from forests was counted as emissions, contributing almost half of the total emissions of the region. As C accumulated into forest vegetation and mineral forest soil, forests were the only land cover class with higher sinks than emissions (Table A11). Because of their large surface area in the river basin (66%), the C sink of the forests decreased the total emissions of the region by 72%, from 15.90 to 4.37 Tg CO_2-eq yr^{-1}.

An example map of the area around the city of Tampere in Pirkanmaa region is plotted in Fig. 3, showing the emissions per unit area for lakes, rivers, undrained mires, arable land, forests and artificial surfaces (g CO_2-eq m^{-2} yr^{-1}). Sharing the spatially explicit information in a series of maps, using an interface with zooming and panning functions, may facilitate visualisation. Details of a draft map series is given in Table A12.

3.2. Artificial surfaces

Anthropogenic emissions in Kokemäenjoki river basin originated from point sources and areal sources relating to artificial surfaces (Fig. 4, Tables 2, A11). The point sources of emissions from fuel combustion in energy production and industrial plants were estimated to 2.87 ± 0.03 Tg CO_2-eq yr^{-1}. Here CO_2 was the dominant gas (99%), with CH_4 about one permille and N_2O about 1% of total emissions. For the area classified as artificial surfaces, 1331 km^2, the anthropogenic emissions were 2.58 ± 0.08 Tg CO_2-eq yr^{-1}. The main emission source was CO_2 from traffic exhaust (71%). Machinery and small-scale combustion also contributed CO_2, each 14% of total emissions. Emissions of CH_4

Table 2
GHG emissions and emission intensities by land use in Kokemäenjoki river basin.

Sources	Area (km^2)	Total emission (±uncertainty) (Tg CO_2-eq yr^{-1})	Emission intensity (Gg CO_2-eq km^{-2} yr^{-1})
Artificial surfaces, point sources			
Liquid (CO_2, CH_4, N_2O)		0.5 (±0.02)	
Waste and other solid (CO_2)		0.15 (±0.003)	
Gaseous (CO_2)		1.41 (±0.01)	
Peat (CO_2, CH_4, N_2O)		0.8 (±0.02)	
Biomass/Wood (CH_4, N_2O)		0.01 (±0.004)	
Artificial surfaces, point sources, total		2.87 (±0.03)	
Artificial surfaces, area sources			
Residential heating, oil (CO_2)	1331	0.35 (±0.02)	0.26
Residential heating, wood (CH4, N2O)	1331	0.03 (±0.05)	0.02
Road transport (CO2)	1331	1.84 (±0.06)	1.38
Machinery, other transport (CO2)	1331	0.35 (±0.02)	0.26
Artificial surfaces, area sources, total	1331	2.58 (±0.08)	1.94
Artificial surfaces total	1331	5.45 (±0.09)	4.09
Aquatic ecosystems			
Lakes (CO_2, CH_4)	2933	0.59 (±0.10)	0.20
Rivers (CO_2)	98	0.54 (±0.15)	5.51
Aquatic ecosystems, total	3031	1.14 (±0.18)	0.38
Mires (CO_2, CH_4, N_2O)	524	0.11 (±0.03)	0.21
Peat extraction sites (CO_2, CH_4, N_2O)	96	0.15 (±0.06)	1.56
Arable land			
Cropland, organic soil (CO_2, N_2O)	182	0.57 (±0.09)	3.13
Cropland, mineral soil (CO_2)	3738	0.08 (±0.05)	0.02
Cropland, total	3920	0.65 (±0.11)	0.17
Agricultural, enteric fermentation (CH_4)	3920	0.34 (±0.06)	0.09
Agricultural, manure (N_2O)	3920	0.17 (±0.21)	0.04
Arable land, total	3920	1.17 (±0.24)	0.30
Forests, NEE (CO_2)	17,782	−11.48 (±1.15)	−0.65
Forests, removals (CO_2)	17,782	7.82 (±0.78)	0.44
Forests, total	17,782	−3.65 (±1.39)	−0.21
Other	441	0	0
Total	27,125	4.37 (±1.43)	0.16

and N_2O from small-scale wood combustion were of minor importance, 1.0 and 0.2% of total emissions. Altogether the point source emissions (53%) and area emissions (47%) amounted to a total of 5.45 ± 0.09 Tg CO_2-eq yr^{-1} of anthropogenic emissions in Kokemäenjoki river basin (Table 2).

3.3. Aquatic ecosystems

3.3.1. Lakes

The total emission of GHGs to the atmosphere from all lake surfaces in the region was 0.59 ± 0.10 Tg CO_2-eq yr^{-1}. Despite their small number, 41 out of a total of 14,804, emissions from lakes in the fourth size class (10–100 km^2) contributed 35% of total emissions because of their large surface area, 44% of total lake area 2933 km^2. Evasion of CO_2 from lake surfaces contributed the largest fraction (82%) of emissions of GHGs from lakes. Fluxes of CH_4 mediated by emergent aquatic macrophytes contributed 10% of total lake emissions, while diffusion and ebullition of CH_4 from lake surfaces stood for 8%.

3.3.2. Rivers

The rivers in the region (Fig. 5) emitted in total 0.54 ± 0.15 Tg CO_2-eq yr^{-1} from their surface areas to the atmosphere. The narrowest streams (<5 m wide) were highest in number (90%) and in emissions (68%), while their surface area represented 37% of the total. The widest river segments (>30 m) contributed only 12% of all river emissions, despite their surface area being about 40% of the total river segment surface area.

3.3.3. Fluxes from terrestrial to aquatic

The total leaching of carbon with river waters to the sea from the river basin was estimated to 0.3 Tg CO_2-eq yr^{-1}. This number is based on the monitoring data for Finnish rivers (Räike et al., 2016), according to which the Kokemäenjoki river (basin number 35) transports altogether 104,300 metric tonnes organic (72%) and inorganic (28%) carbon into the Gulf of Bothnia. Based on the upscaling of the INCA-C application to the Pääjärvi catchment within the Kokemäenjoki river basin, the amount of organic carbon leaching from mires, cropland, and forests to the watercourses was estimated to correspond to about 10% of the CO_2 and CH_4 emissions from land to air.

3.4. Undrained mires and peat extraction sites

For a total area of 524 km^2 of undrained mires in the Kokemäenjoki river basin 102,060 spatial units were identified as either minerotrophic or ombrotrophic, covering 61 and 39% of total undrained mire area, respectively (Fig. 6). Only about 0.1 km^2 was not clearly identified into either type. These 74 unidentified spatial units were excluded from the calculations. The total net emissions were 0.11 ± 0.03 Tg CO_2-eq yr^{-1} (Table 2), calculated from emissions of CH_4 (0.16 ± 0.03) and N_2O (0.01 ± 0.003) and a C sink corresponding to negative CO_2 emissions of −0.06 ± 0.01 Tg CO_2-eq yr^{-1}. The share of CH_4 and N_2O emissions were 93 and 7%, respectively, of the total emissions, while the carbon sink associated with the negative CO_2 emissions decreased the total emissions with 36%. Minerotrophic mires contributed 64% of the carbon sink, and their share of the net emissions was 72%.

For the total area of 96 km^2 of peat extraction use, the CO_2 emissions of peatland were 0.14 ± 0.06 Tg CO_2-eq yr^{-1}, CH_4 emissions 0.005 ± 0.002 Tg CO_2-eq yr^{-1} and N_2O emissions 0.009 ± 0.003 Tg CO_2-eq yr^{-1}. Thus, the total emissions from peatland used for peat extraction equalled 0.15 ± 0.06 Tg CO_2-eq yr^{-1}.

3.5. Arable land

Arable land emissions (Fig. 7) included those of CO_2 and N_2O from agricultural soils, as well as CH_4 from enteric fermentation and N_2O from manure in domestic livestock units of the agricultural sector. The cropland area soil type was classified as organic or mineral, with total estimated areas of 182 km^2 and 3738 km^2, respectively, in total 3919 km^2 in Kokemäenjoki river basin.

Cultivation on organic agricultural soils caused N_2O emissions of 0.09 ± 0.03 Tg CO_2-eq yr^{-1}. About 76% of these were from fields with annual plants, and 24% from growing perennial plants. The soil emissions of CO_2 were estimated to 0.08 ± 0.05 Tg CO_2-eq yr^{-1} for mineral and 0.48 ± 0.09 Tg CO_2-eq yr^{-1} for organic soils. The total organic soil emissions (CO_2 and N_2O) were thus 0.57 ± 0.09 Tg CO_2-eq yr^{-1}. Thus, the organic soils represented 5% of the cropland area and 88% of total cropland soil emissions of the study site, while the mineral soils represented 95% of the cropland area and 12% of the total cropland soil emissions. The sum of mineral and organic soil cropland emissions resulted in 0.65 ± 0.11 Tg CO_2-eq yr^{-1}.

Domestic livestock production caused emissions of CH_4 (from enteric processes) amounting to 0.34 ± 0.06 Tg CO_2-eq yr^{-1} and fertilization emissions of N_2O of 0.17 ± 0.21 Tg CO_2-eq yr^{-1}. These area emission sources, calculated with the FRES model, were divided evenly over the surface area of arable land. The total emissions in arable land included emissions from mineral and organic cropland soils, cattle production and fertilization, amounting in total to 1.17 ± 0.24 Tg CO_2-eq yr^{-1}.

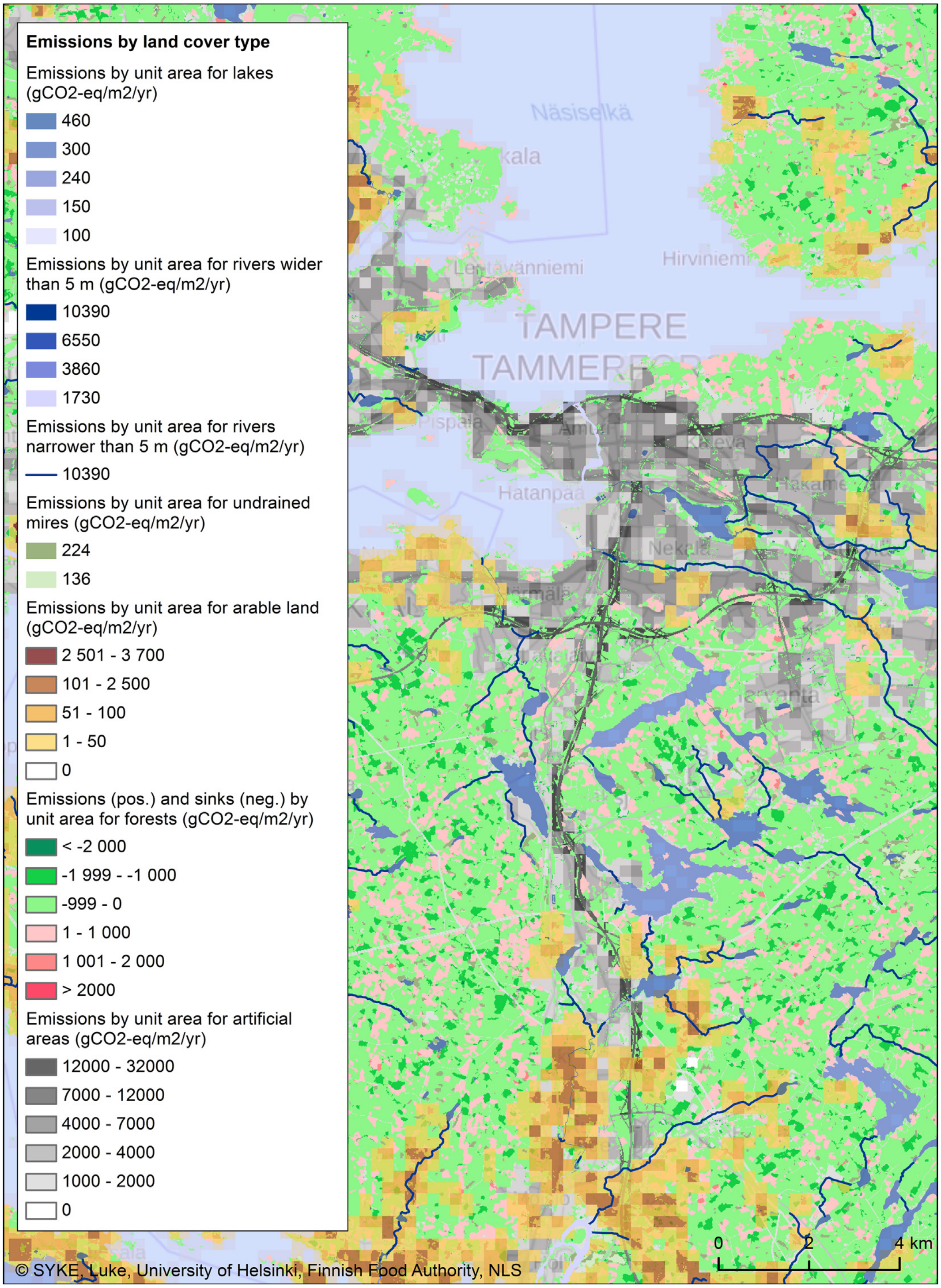

Fig. 3. Emissions of all land cover types (g CO_2-eq m^{-2} yr^{-1}) around the city of Tampere in Pirkanmaa region.

3.6. Forest

The average NEE of forests on mineral soil and drained peatland in the region was -176 ± 17.6 g C m^{-2} yr^{-1}. Forest mineral soils were a sink of carbon, on average. Wood removals from forests were 120 ± 12 gC m^{-2} yr^{-1}, on average. Over the whole study region, the carbon sink of the forests (including forests on drained peatland) was -11.48 ± 1.15 Tg CO_2-eq yr^{-1}, while the removals contributed emissions of 7.82 ± 0.78 Tg CO_2-eq yr^{-1}, and the net sink of the forest became -3.65 ± 1.39 Tg CO_2-eq yr^{-1}. The forests thus contributed the only significant sink of the region, on average -0.21 Gg CO_2-eq km^{-2} yr^{-1}.

4. Discussion

4.1. River basin

The approach presented here differs in many respects from that of the national GHG inventory report (Statistics Finland, 2020). Most

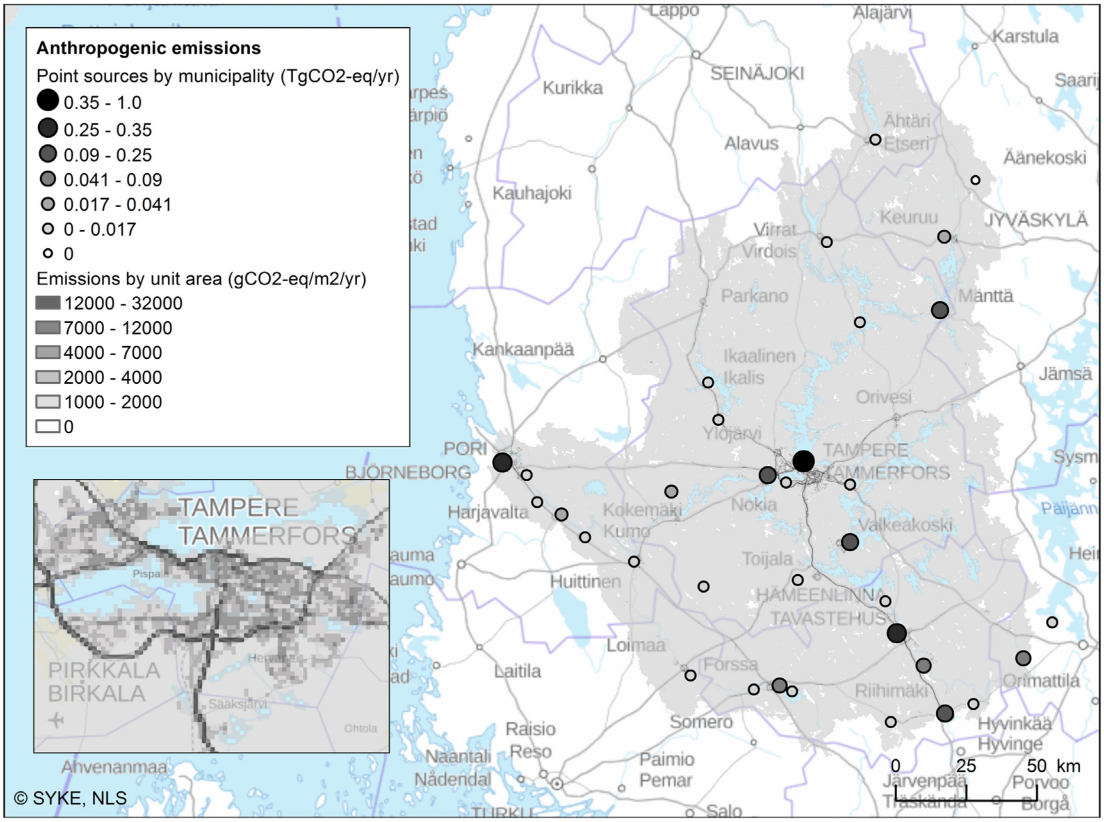

Fig. 4. Anthropogenic emissions from point sources and area sources relating to artificial surfaces in Kokemäenjoki river basin.

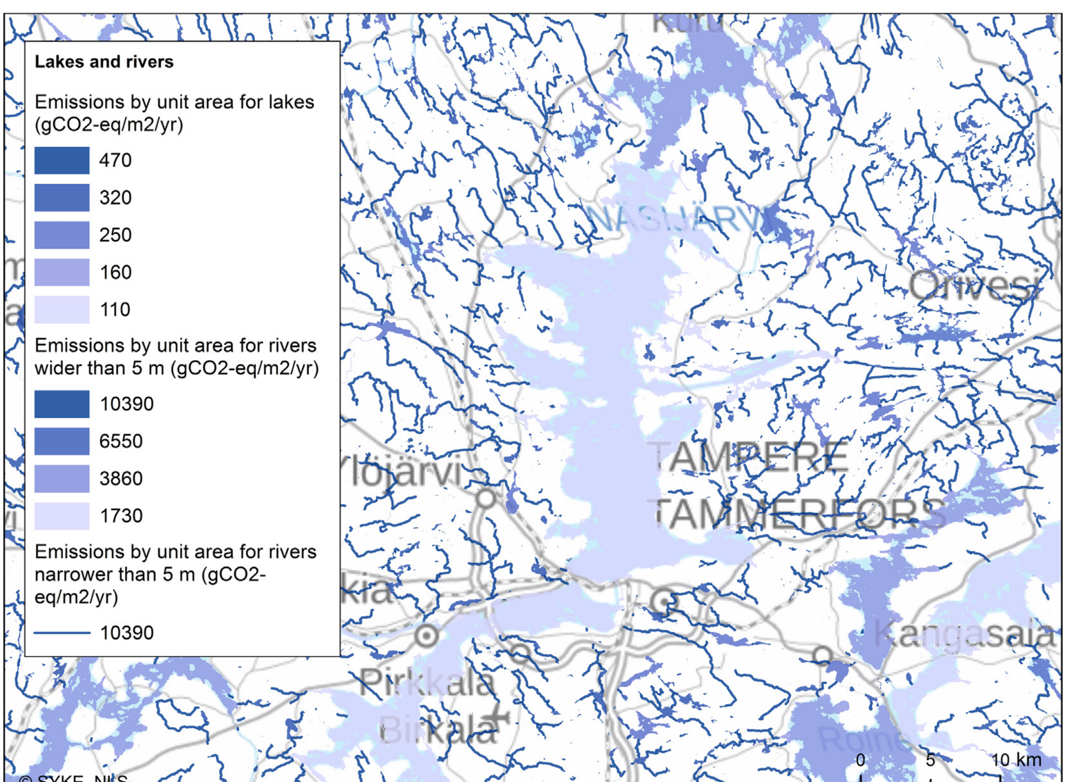

Fig. 5. Spatial distribution of emissions by unit area from lakes (five size classes) and rivers (four size classes) in Kokemäenjoki river basin. View from the surroundings of Tampere city, Pirkanmaa region, with lakes Näsijärvi and Pyhäjärvi in the centre.

Fig. 6. Spatial distribution of undrained mires of minerotrophic and ombrotrophic types. View from the surroundings of Puurijärvi, east of Kokemäki city, Satakunta region.

importantly, our objective is different. While the national report is an official mandatory activity regulated by international agreements and national legislation, drawing on annually compiled statistical data covering the whole country, our paper is an attempt to present an estimate of the relative importance of different land use classes for the net GHG emissions of a river basin. We consider only partly the same sectors as the national inventory (fuel combustion in the energy sector, domestic livestock production in the agriculture sector, undrained mires, peat extraction sites, and cropland soils). The national inventory uses statistical data to derive emissions of the energy sector, and agriculture, while we use the FRES-model for fuel combustion emissions and domestic livestock production emissions. Statistics on forest biomass, and the YASSO07-model for mineral soils, are used in the national inventory, where we used the PREBAS-model, with YASSO07 included,

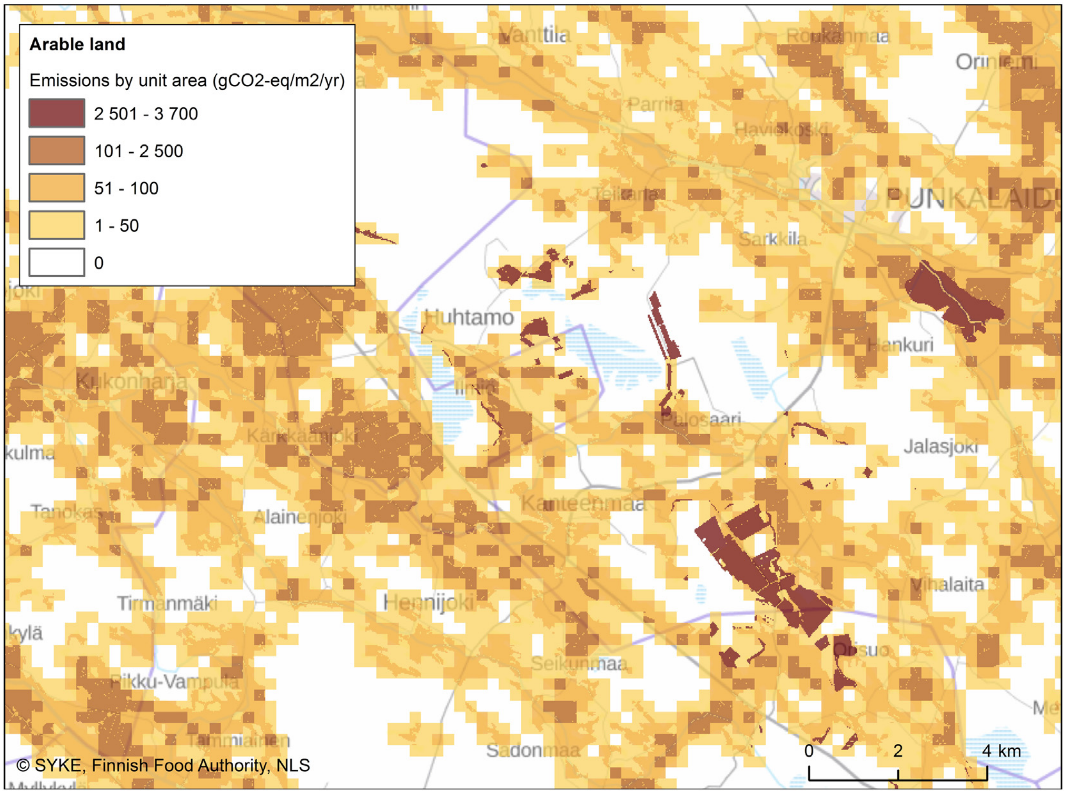

Fig. 7. Emissions by unit area (g CO_2-eq m^{-2} yr^{-1}) for arable land. View of the surroundings of Huhtamo on the border between the Pirkanmaa (east) and Satakunta (west) regions.

for forest emissions and sinks. The area-based emission factors we used for peat extraction sites and cropland soils were from the national inventory (Statistics Finland, 2020). Lakes and rivers are included as wetlands in the national inventory and their emissions are based on changes in their area or biomass, while we calculated emissions for lakes and rivers based on emission coefficients from the literature.

From the national GHG inventory, an average net emission of 47.9 Tg CO_2-eq yr^{-1} can be estimated for the emissions reported for the period 1990–2018 (Statistics Finland, 2020). With an average population for the same period of 5,360,809 persons, and a total land area of 303,921 km^2, the national average per capita becomes 8.9 Mg CO_2-eq yr^{-1}, with a corresponding net areal emission intensity of 0.16 Gg CO_2-eq km^{-2} yr^{-1}. The Kokemäenjoki river basin covers an area of about 8% of the country total, and its population in 2020 represented about 14% of Finland's. In our analysis, the net areal emission intensity was 0.16 Gg CO_2-eq km^{-2} yr^{-1}, and the net per capita intensity was 5.6 Mg CO_2-eq yr^{-1}. In the national inventory, the energy sector represented 76% of total emissions, excluding the land use, land use change and forestry sector. For Kokemäenjoki, fuel combustion stood for 80% of emissions, not including emissions from lakes, rivers, and forests.

In our approach, we summed the vertical fluxes of spatially explicit net emissions, disregarding the lateral fluxes from terrestrial to aquatic ecosystems. Thereby our regionally aggregated net emissions 4.37 ± 1.43 Tg CO_2-eq yr^{-1} did not reflect the observed riverine transport of C to the sea (0.3 Tg CO_2-eq yr^{-1}, Räike et al., 2016), or the approximated leaching of organic C from mires, cropland and forests to the watercourses (Section 3.3.3). For a fully integrated regional GHG budget, however, all lateral fluxes of C- and N-containing compounds would need to be accounted for, e.g., those caused by erosion, leaching, riverine transport, food and product trade, human travel, and atmospheric transport of reduced C compounds emitted from ecosystems and anthropogenic activities (CO, CH4, biogenic and anthropogenic volatile organic compounds), as demonstrated on the continental scale in Europe (EU-25) by Ciais et al. (2008), who estimated lateral transport fluxes of C to amount to 165 Tg C yr^{-1}, exceeding the terrestrial C uptake by ecosystems (111 ± 279 Tg C yr^{-1}, Janssens et al., 2003). The lateral fluxes were omitted in our study, because a quantitative incorporation of both vertical and lateral transport would have required, as a minimum, applying a catchment-scale dynamic model of C processes (e.g. Forsius et al., 2017), or even incorporating the hydrological cycle with the connectivity of C, N and phosphorus (P) cycles (Nakayama, 2017), and furthermore, also accounting for lateral transport caused by, e.g. food and product trade, and atmospheric circulation, which topics were beyond the scope of this paper.

4.2. Lakes

The GHG emissions from lakes may be greater than reported here, as we did not include N_2O emissions from lakes. Assuming an estimate for N_2O fluxes of 35% of the diffusive CH_4 emissions (Kortelainen et al., 2020), the missing source would be about 1% of the total emissions from lakes in our region. We assumed a maximum of 5.3% of the lake surface to be vegetation covered, disregarding the fact that there are four lakes invaded with vegetation to about 50 or 80% of their surface area, which would imply about 3 times higher CH_4 emissions from these four lakes. The vegetation invaded lakes have a total surface area of 0.2% of the river basin's total lake area.

4.3. Cropland

The fraction of annual plant cultivation area in actively used fields with organic soils is more than the average in Finland, 37.6%. The fraction of organic soils from the total of field areas in active use, both mineral and organic soils, is 4.65% in Kokemäenjoki river basin, while on the average it is 11.0% in Finland (Regina et al., 2019). Preferring cultivating mineral over organic soils offers a good mitigation potential (e.g.

Tanneberger et al., 2021). In the river basin, half of the GHG emissions from agricultural activities originated from cultivating cropland on organic soils that represent less than 5% of the entire arable land in the region.

4.4. Forest

The simulated estimates of forest growth and carbon balance were comparable with national level data. The mean annual growth in the Kokemäenjoki river basin was 7.1 m^3 ha^{-1} yr^{-1} which was similar to the observed mean in southern Finland, 6.9 m3 ha^{-1} yr^{-1} in 2014–2018 (Natural Resources Institute Finland, 2020). The simulated NEE of forests, 176 g C m^{-2} yr^{-1}, was also close to the national mean, 178 g C m^{-2} yr^{-1} in 2018, supporting the validity of the PREBAS modelling framework. The net C sink of forest is determined by the balance between annual C sequestration and harvest removals. It was 56 g C m^{-2} yr^{-1} falling into the range of the national estimate, 31 to 60 g C m^{-2} yr^{-1} in 2009–2017 (Statistics Finland, 2020; Natural Resources Institute Finland, 2020). At the national level, the fluctuation of annual growth is less than that of harvest rates, which depend on the international market of wood products.

We note that our estimates of lateral C fluxes from terrestrial to aquatic ecosystems were not coupled to our calculations of vertical fluxes from vegetation, soil and water surfaces to the atmosphere. For example, the heterotrophic respiration estimates on mineral forest soils were produced with a soil carbon model, YASSO07, which assumed no carbon leaching out of the forest ecosystem. Parameterising the model was based on the weight loss of different soil organic matter (SOM) components, assuming that weight loss was due to release of CO_2 into the atmosphere. This can be regarded as double-counting of emissions, because we also accounted for release of leached organic carbon through water bodies. The average leaching of organic carbon from forests to water bodies in Finland has been estimated to be about 10 gC m^{-2} yr^{-1} (Finér et al., 2021), i.e., less than 5% of our estimate of average NEE in the forested area. Furthermore, the potential double counting may be at least partly counter-balanced by a respective underestimation of autotrophic respiration, because the total carbon balance has been tested against net ecosystem exchange, albeit at very few flux sites where data has been available. While a lot of research is still needed for a proper quantification of the carbon fluxes between forest soils and waters (e.g., Chapin III et al., 2006), we trust that the related error here is captured by the error margin estimates presented above.

4.5. Uncertainty

The only sources of uncertainty considered in this analysis were uncertainty in the emission coefficients. The emission coefficients were chosen to be the best available and most recent for the given geographical location and land cover class. The ranges of uncertainty of the emission coefficients were assumed to cover the possible temporal and spatial variation of each land cover type emission coefficient within the given geographical location.

The uncertainty analysis carried out did not cover uncertainty in spatial allocation of the emission sources in the different land cover classes (artificial surfaces, lakes and rivers, undrained mires, peat extraction sites, arable land, and forest). Furthermore, we did not deal with the uncertainty in estimates of land cover class specific spatial areas, caused by the classification and segmentation of the pixel level map data to different land cover class areas. On the level of pixels, or individual locations, the local emission estimate can be assumed to be highly uncertain, since a small area cannot be exactly estimated from a map of a given resolution, and the actual land cover class and the activity data of the distinct location may sometimes differ greatly from the regional statistical averages. On the regional level, on the other hand, these uncertainties can be assumed smaller. More research is, however, needed to validate the emission uncertainty caused by uncertainty in activity data and area estimation at different spatial scales (local, regional and global scale).

The simulated emissions over the forested areas bear uncertainties related to the PREBAS-model structure and parameters, the initial status of forests based on the MS-NFI data, and the allocation of harvests to the forest parcels. The k-Nearest Neighbour algorithm of the MS-NFI averages stand volumes and site fertility classes, levelling off extremes (Tomppo et al., 2008a, 2008b). Therefore, the simulation results are more reliable in the landscape level than on individual grid cells of forest management units. The total harvest level was set based on the statistics of harvest removals in the river basin. However, the allocation of harvests to the forest parcels followed the guidelines of forest management, independent of the true forest management operations in the study area. Therefore, the results are not accurate at the level of individual forest estates but represent a simulated development limited to certain assumptions. We consider that aggregated totals and means over the area are not sensitive to the exact spatial attribution of harvests.

4.6. Application

Mitigating global climate change and adapting to its long-term consequences is an imminent challenge requiring actions at different spatial scales, ranging from local to global. Municipalities and other regional actors are often able to make decisions that affect local GHG emissions and sinks. Comprehensive detailed spatial information on the GHG budget and its uncertainties is needed for mitigating GHG emissions via planning, management and decision-making (e.g. Vanhala et al., 2016). GHG balances in different land-use classes are strongly dependent on the site characteristics, and these uncertainties can be better quantified and reduced using detailed spatially explicit data sets. GHG budget calculations are also useful for identifying which landscape elements are most likely to reveal changes in C fluxes in response to climate and land use changes in the future (Buffam et al., 2011). Although we recognize the value of a fully integrated GHG balance, incorporating vertical and lateral fluxes (Chapin III et al., 2006; De Wit et al., 2015; Nakayama, 2017), we regard our approach as an effective means to aggregate the vertical fluxes for a selected region of various sizes and boundaries.

5. Conclusions

We determined spatially explicit estimates of GHG emission sources and sinks at the landscape scale using models for artificial surfaces and forests; and area-specific emission factors for lakes, rivers, undrained mires, peat extraction sites and arable land. Artificial surfaces were the most emission intensive land cover class, including point sources emissions from fuel combustion in energy production and industrial plants; and traffic exhausts, representing about one third of the region's total emissions. Lakes and rivers were about as emission intensive as arable land. Cultivation of organic soils stood for half of the emissions from agricultural activities. Undrained mires were less emission intensive but with an insignificant surface area they had not a large effect on the average emission intensity of the river basin. Forests were the largest land cover class (66%). The accumulation of C into forest biomass and mineral forest soil was an important sink which decreased the region's emissions with 72% of the total emissions. As a result, the Kokemäenjoki river basin was an annual net emission source of 4.37 ± 1.43 Tg CO_2-eq yr^{-1} of greenhouse gases CO_2, CH_4 and N_2O. The method we presented is readily applicable to other regions, and other aggregation boundaries, for example administrative units, and to the country level.

CRediT authorship contribution statement

Maria Holmberg: Conceptualization, Methodology, Software, Validation, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Anu Akujärvi: Validation, Formal analysis, Investigation, Writing – review & editing. **Saku Anttila:** Methodology, Software, Formal analysis, Investigation, Data curation, Funding acquisition. **Iida Autio:** Methodology, Formal analysis, Investigation, Data curation, Visualization. **Markus Haakana:** Software, Data curation. **Virpi Junttila:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – review & editing. **Niko Karvosenoja:** Methodology, Formal analysis, Funding acquisition. **Pirkko Kortelainen:** Methodology, Writing – review & editing. **Annikki Mäkelä:** Methodology, Software, Formal analysis, Writing – review & editing, Funding acquisition. **Kari Minkkinen:** Methodology. **Francesco Minunno:** Methodology, Software, Formal analysis, Writing – review & editing. **Katri Rankinen:** Formal analysis, Writing – review & editing. **Paavo Ojanen:** Methodology, Formal analysis, Writing – review & editing. **Ville-Veikko Paunu:** Methodology, Software, Formal analysis. **Mikko Peltoniemi:** Methodology, Data curation, Writing – review & editing. **Terhi Rasilo:** Methodology. **Tapani Sallantaus:** Methodology, Writing – review & editing. **Mikko Savolahti:** Methodology, Formal analysis. **Sakari Tuominen:** Formal analysis, Writing – review & editing. **Seppo Tuominen:** Formal analysis. **Pekka Vanhala:** Methodology. **Martin Forsius:** Conceptualization, Writing – review & editing, Funding acquisition.

Declaration of competing interest

We have no known competing financial interests or personal relationships that have influenced the work reported in this paper.

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Appendix A. Supplementary data

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